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Ionospheric constraints on VHF/UHF communications links during solar maximum and minimum periods

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An extensive VHF/UHF scintillation data base covering the frequency range of VHF to a few gigahertz has been utilized to determine the magnitudes of phase and intensity scintillations and their temporal/spatial structures during the sunspot maximum and minimum periods. The equatorial portion of the study has been based on geostationary satellite observations at Huancayo, a station on the magnetic equator, and at Ascension Island, which is an equatorial anomaly station having an extremely disturbed irregularity environment. The high-latitude part of the study is based on quasi-stationary satellite measurements at a polar cap location (Thule) and two auroral locations (Goose Bay and Tromsø). The Tromsø observations are augmented with the Defense Nuclear Agency HiLat satellite beacon measurements during the solar minimum period. The data indicate a strong solar cycle control of scintillation activity at all locations, resulting in a drastic reduction of the magnitudes and occurrence of scintillations during the current solar minimum period. This pattern is consistent with both a reduction of F region ionization density and a reduction of irregularity generation in the solar minimum period. At the magnetic equator the magnitude of scintillations at 1.5 GHz seldom exceeds 3 dB with the percentage occurrence >2 dB varying from 70% during high sunspot conditions to 30% during low sunspot conditions. At the crest of the equatorial anomaly, on the other hand, during the solar maximum in 1979, fades of 20 dB at 1.5 GHz are observed 30% of the time. At a decreased level of solar activity in 1982, a similar occurrence level is obtained at 1.5 GHz for fade levels of only 5 dB. During the solar minimum period, 1.5-GHz scintillations are virtually absent. Phase scintillation measurements made at Ascension Island indicate that the median value of rms phase deviation is about 5 rad for detrend intervals of 100 s. In the auroral region, during the solar maximum period under magnetically disturbed conditions, the median values of scintillation fades and rms phase deviation (82-s detrend) at 250 MHz are observed to be 15 dB and 3 rad, respectively. At Thule, located deep within the polar cap, the median values of scintillation fades and rms phase deviation at 250 MHz attain values as large as 20 dB and 4 rad during the sunspot maximum period. Unlike Ascension Island the scintillation activity at high-latitude stations exhibits a threshold effect and does not decrease until 1983. However, in 1986 with sunspot numbers in the vicinity of 10, fade levels as low as 5 dB at 250 MHz are recorded in the polar cap and auroral stations only 5% of the time. It is noted that at auroral locations the most prominent feature, namely the existence of magnetic L shell-aligned irregularity sheets, is equally evident at both sunspot maximum and minimum.

INTRODUCTION

Satellite communication links in the VHF/UHF range can suffer severe scintillation effects in amplitude and phase due to the presence of irregularities in electron density in the F region of the ionosphere. The magnitude of random phase perturbations imposed on a transionospheric communication link depends on the integrated electron density deviation, $\int \Delta N \, dl$, along the ray path. It may be shown that this parameter is controlled by the irregularity amplitude ($\Delta N/N$) and the background electron density, N, and its distribution in the ionosphere. Satellite in situ measurements have shown that while the irregularity amplitude remains fairly constant the background density in some regions of the globe undergoes a drastic variation with the sunspot cycle. This in turn has a profound effect on the magnitude of intensity

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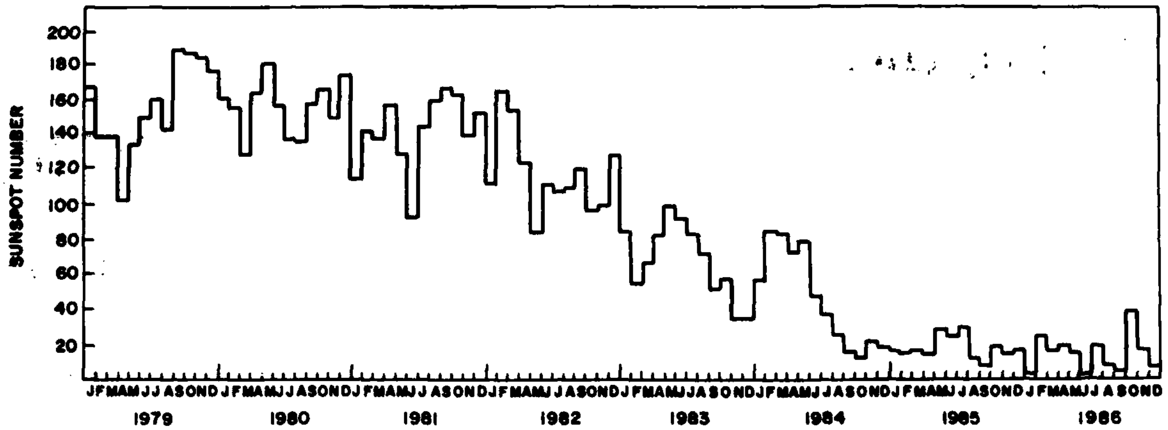

Fig. 1. Variation of monthly mean sunspot number between 1979 and 1986.

and phase scintillations as a function of the sunspot cycle at any point on the globe. Furthermore, the occurrence of irregularities may be reduced with decreasing solar activity, for instance, as a result of the decreased height of the *F* region, and, as such, the percent occurrence of scintillations may decrease with decreasing solar activity. The object of this paper is to describe the observed variation of scintillations as a function of sunspot cycle within the major scintillation-producing regions of the globe using the extensive archive of such data at the Air Force Geophysics Laboratory (AFGL).

RESULTS

We shall present phase and amplitude scintillation data from the solar maximum to minimum period (1979–1986) observed from Huancayo, a station on the magnetic equator, from Ascension Island, an equatorial anomaly station, from Goose Bay and Tromsø, both auroral locations, and from Thule situated deep within the polar cap. Figure 1 shows the nature of variation of the sunspot number between 1979 and 1986 with the maximum value being 190 in August 1979 and the minimum about 2 in June 1986. Table 1 lists positions of stations and ionospheric intersection latitudes (in corrected geomagnetic (CG) system) of the measurements at each station.

Huancayo

The occurrence statistics of 137-MHz scintillations as a function of solar cycle at Huancayo were presented by *Aarons* [1977]. The occurrence shows a diffuse maximum from October through March with only a slight decrease seen in December. Scintillations were practically nonexistent during the June solstice for quiet magnetic activity. The occurrence did not vary significantly as a function of solar cycle, the maximum equinoctial occurrence being reduced to 60% occurrence greater than 6 dB in comparison to 80% during sunspot maximum. It was felt that because of saturation effect at 137 MHz, a similar study was necessary at a higher frequency. *Su. Basu et al.* [1980] presented the occurrence statistics of 1.5-GHz scintillations observed at Huancayo during the sunspot minimum period of 1976–1977. The seasonal pattern showed clear equinoctial peaks with 30% occurrence of scintillations greater than 2 dB observed during March and October. Figure 2 shows the corresponding scintillation statistics for the high-sunspot period of 1979–1980. Only the occurrence of scintillations during the vernal equinox was found to increase (from 30 to 60%) in comparison to the low-sunspot case. It is important to note that the magnitude of scintillations was not found to vary significantly as a function of sunspot cycle at the magnetic

TABLE 1. Station Locations and Ionospheric Intersection Latitudes

Station	Geographic Location: Latitude	Geographic Location: Longitude	350-km Intersection CG Latitude
Huancayo	12.0°S	75.3°W	0°
Ascension Island	7.4°S	14.4°W	17°S dip latitude
Goose Bay	53.3°N	60.3°W	64°–69°
Tromsø	69.7°N	18.9°E	66°–69°
Thule	76.5°N	68.7°W	84°–89°

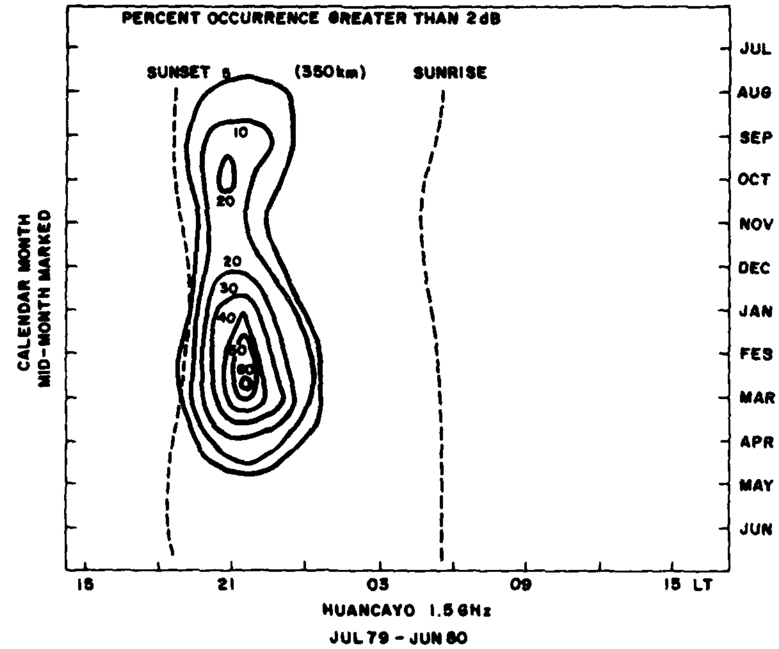

Fig. 2. Percent occurrence of scintillations >2 dB at 1.5 GHz observed at Huancayo during the solar maximum period of July 1979 through June 1980 for $Kp < 3$.

equator. This is quite contrary to scintillation behavior observed at the equatorial anomaly location to be discussed in the next section.

Ascension Island

It has been shown recently that some of the largest propagation disturbances are observed at this location during sunspot maximum years [*Aarons et al.*, 1981*a*; *Mullen et al.*, 1985; *S. Basu et al.*, 1987*a*]. At Ascension Island, continuous amplitude scintillation observations have been performed by the use of 257-MHz and 1.5-GHz transmissions from the Marisat satellite and 244-MHz signal from the Fleetsatcom satellite. Figure 3*a* shows an occurrence diagram of 1.5-GHz scintillations in the premidnight period (2000–2400 LT) for the years 1980–1986. While fades as deep as 20 dB at 1.5 GHz are observed 30% of the time in March 1980, fades of only 10-dB magnitude are observed not more than 10% of the time in October 1983. At the lowest level of the sunspot cycle in 1985–1986, there is virtually no occurrence of 1.5-GHz scintillation. To show that even under sunspot maximum conditions, gigahertz scintillation is a serious problem only in the premidnight hours, we present in Figure 3*b* the corresponding statistics at Ascension Island for the postmidnight period (0000–0400 LT). It should also be noted that gigahertz scintillations are generally not observed at Ascension Island in the May through August period even under sunspot maximum conditions.

In general, all equatorial stations observe high scintillation activity during the equinoxes, but stations in the American and African sectors record minimum activity during the June solstice, and those in the Pacific sector observe a minimum during the December solstice [*Aarons et al.*, 1980]. Attempts have been made to explain this seasonal-cum-longitudinal pattern of equatorial irregularities in terms of transequatorial neutral wind flows [*Maruyama and Matuura*, 1984] and Pedersen conductivity gradients across magnetic flux tubes [*Tsunoda*, 1985]. In this paper, however, we shall confine our attention to the solar cycle variation of scintillations.

In addition to performing multifrequency amplitude scintillation measurements, a computer-controlled phase-locked receiver (designed by M. D. Cousins of SRI International) was used to measure phase and amplitude scintillations of 244-MHz transmissions of the Fleetsatcom satellite over a limited period. The phase scintillation statistics at 244 MHz, expressed in terms of rms phase deviation (σ_ϕ),

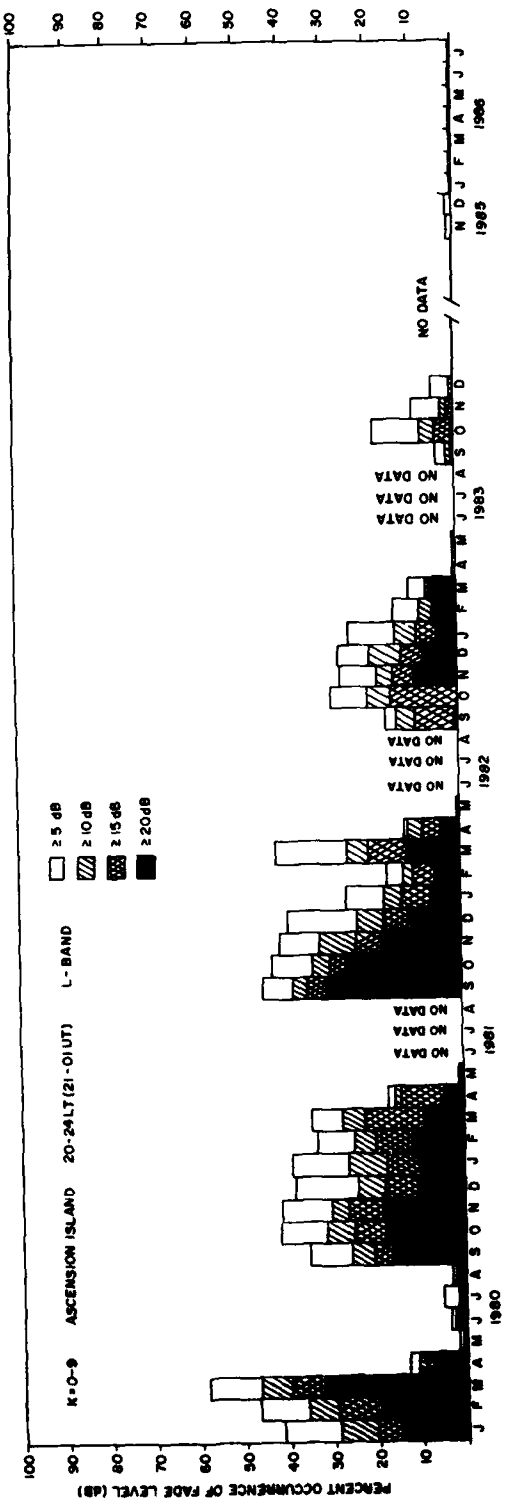

Fig. 3a. Occurrence of 5-, 10-, 15-, and 20-dB fades at 1.5 GHz observed at Ascension Island during 2000–2400 LT (2100–0100 UT) for the period 1980–1986.

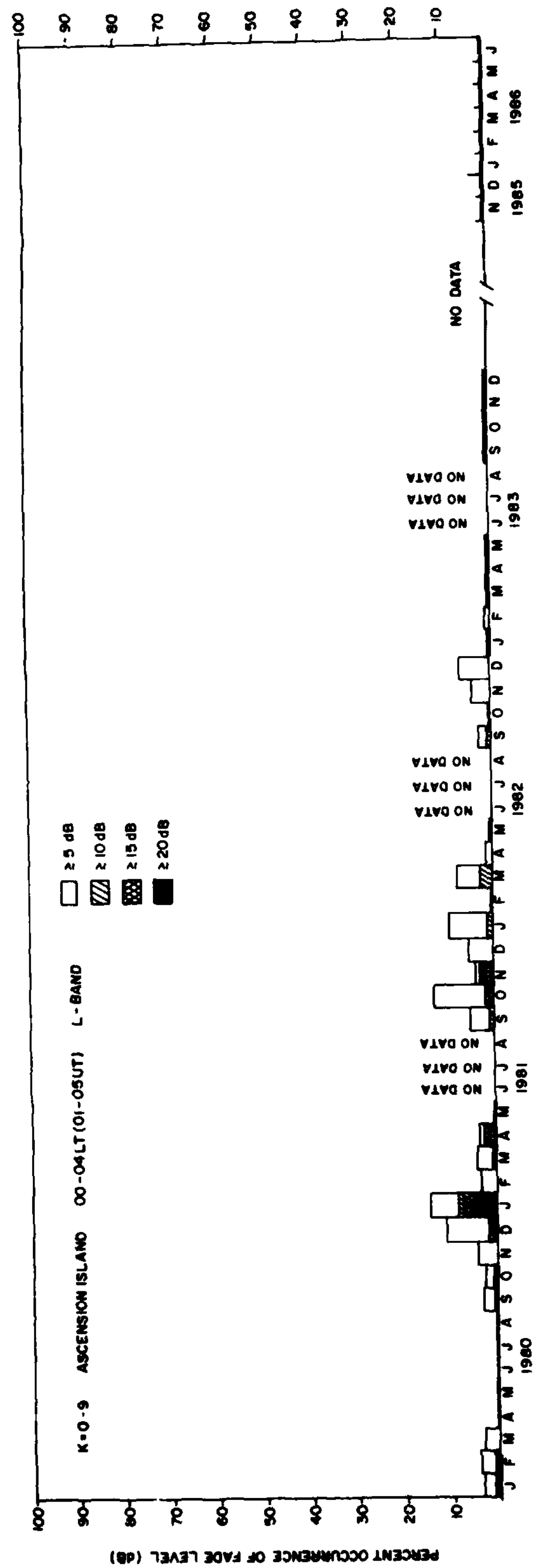

Fig. 3b. Same as for Figure 3a except during 0000–0400 LT (0100–0500 UT).

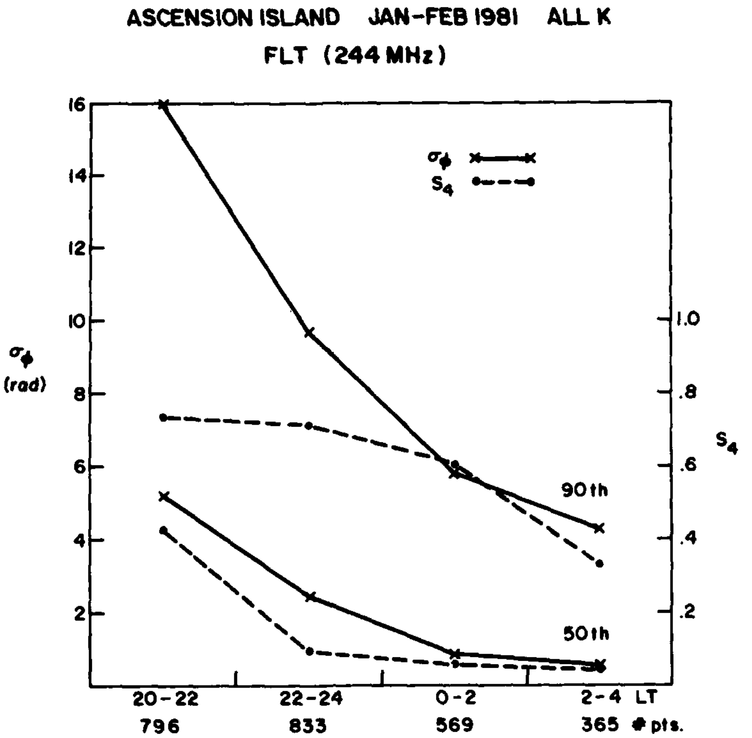

Fig. 4a. The median (50th percentile) and 90th percentile values of phase and intensity scintillations at 244 MHz in terms of four 2-hour blocks of local time (LT) during January–February 1981 at Ascension Island.

during the sunspot maximum period of January–February 1981 are reproduced from *S. Basu et al.* [1987*a*] in Figure 4*a*. In the 2000–2200 LT period the median value of σ_ϕ is shown as 5 rad (for 100-s detrend interval), and the corresponding upper decile is obtained as 16 rad. The intensity scintillation index S_4, defined as the square root of the normalized variance of intensity, is also shown in the figure. The median value of S_4 is about 0.4. In view of the saturation of the receiver encountered at $S_4 \sim 0.7$, the median S_4 is likely to be an underestimate of the actual level of activity. No phase scintillation measurements are available for sunspot minimum conditions.

The other parameters that characterize the structure of scintillations, namely, the decorrelation time and phase spectral strength, were studied for this observing station as well. The decorrelation time has been defined as the time interval that corresponds to the reduction of the autocorrelation coefficient of normalized intensity to 0.5, and the phase spectral strength T_ϕ corresponds to the power spectral density of phase scintillation spectrum at 1 Hz. For intense scintillation events at 244 MHz ($S_4 > 0.6$), Figures 4*b*, 4*c*, and 4*d* show, respectively, the variation of decorrelation time with phase spectral strength and the percent occurrence of each of these parameters within the period 2000–0200 LT in January–February 1981. Figure 4*b* shows that the decorrelation

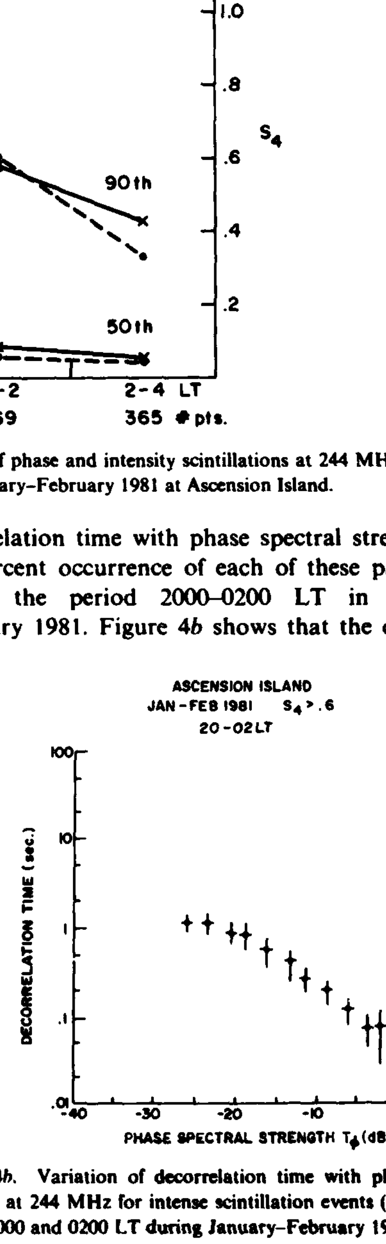

Fig. 4*b*. Variation of decorrelation time with phase spectral strength at 244 MHz for intense scintillation events ($S_4 > 0.6$) between 2000 and 0200 LT during January–February 1981 at Ascension Island.

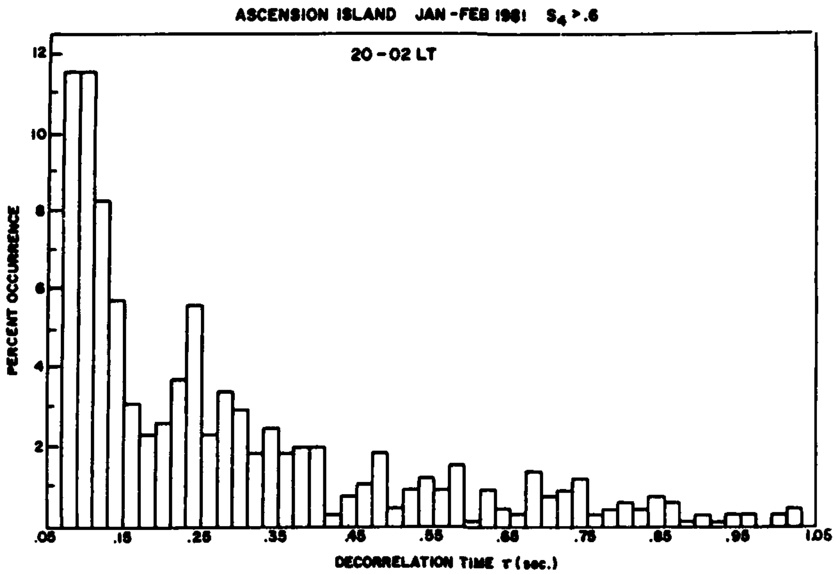

Fig. 4*c*. Distribution of decorrelation times for the data set shown in Figure 4*b*.

tion time decreases in a well-ordered manner with increasing phase spectral strength. This behavior is predicted from strong scattering theory and was demonstrated earlier by *Rino and Owen* [1980]. Figures 4*c* and 4*d* indicate that for this strong scatter population ($S_4 > 0.6$) the most probable value of phase spectral strength is -6 dB and the decorrelation time is about 0.1 s. Since the irregularity drift

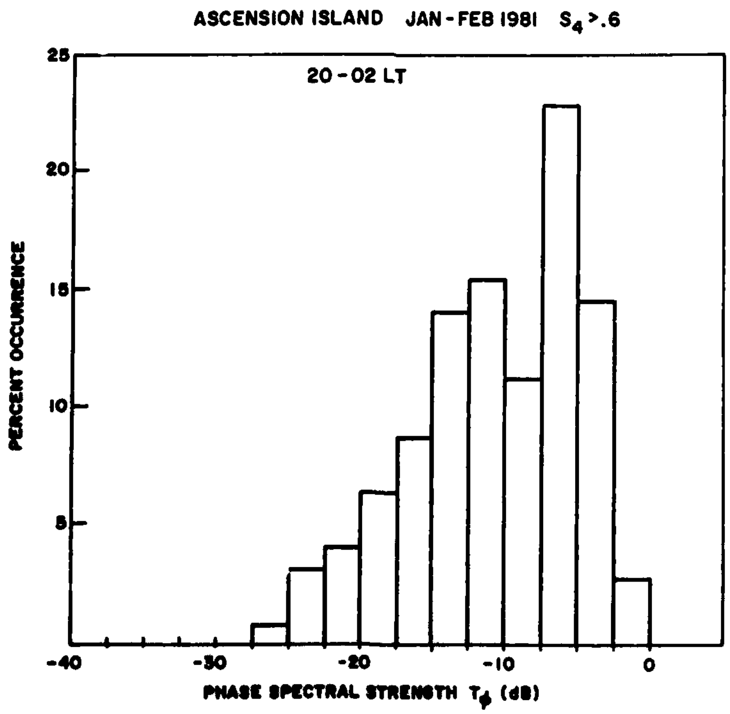

Fig. 4*d*. Distribution of phase spectral strengths for the data set shown in Figure 4*b*.

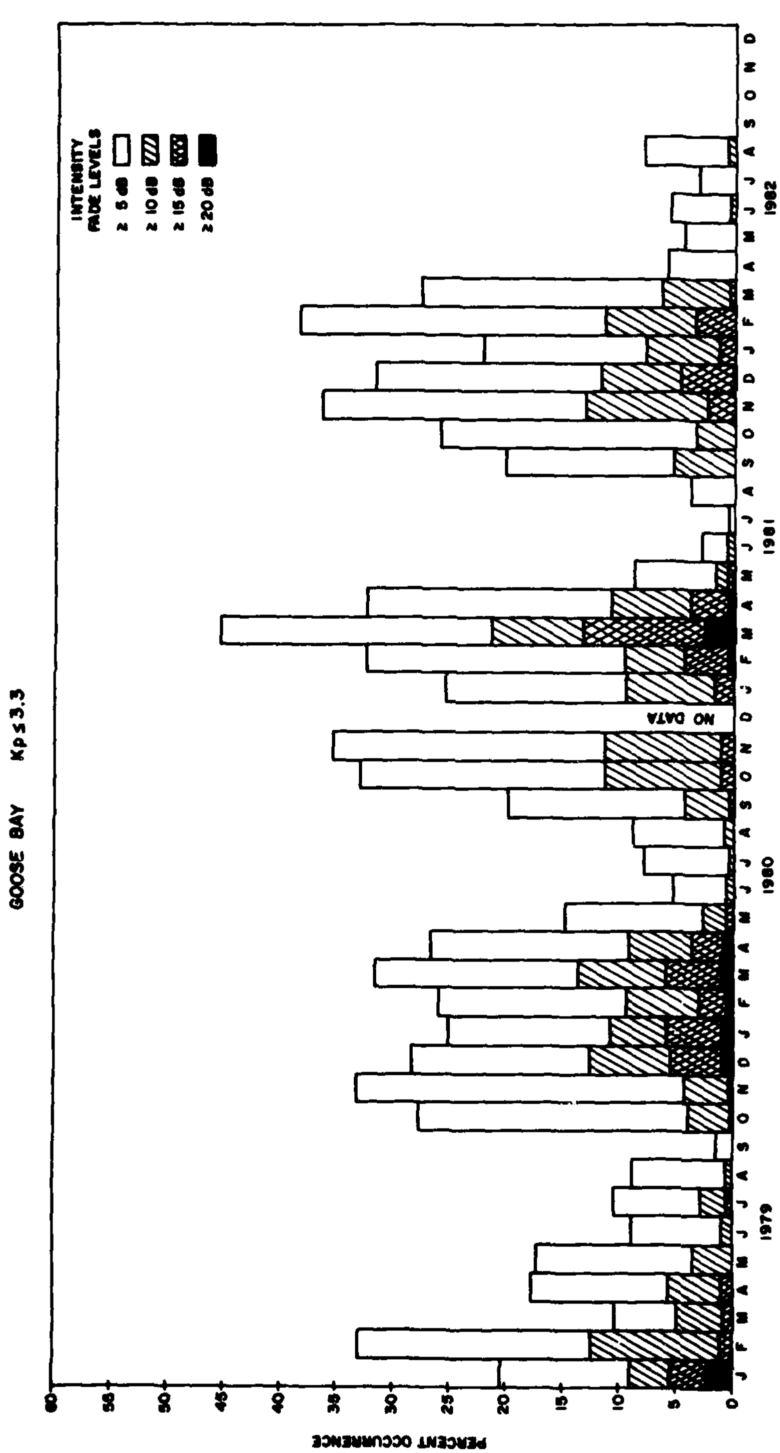

Fig. 5a. Intensity scintillations at 250 MHz observed at Goose Bay for $Kp < 3.3$ under high-sunspot conditions between 1979 and 1982. Note that the apparent seasonal variation may be caused by the latitude variation of the intersection point.

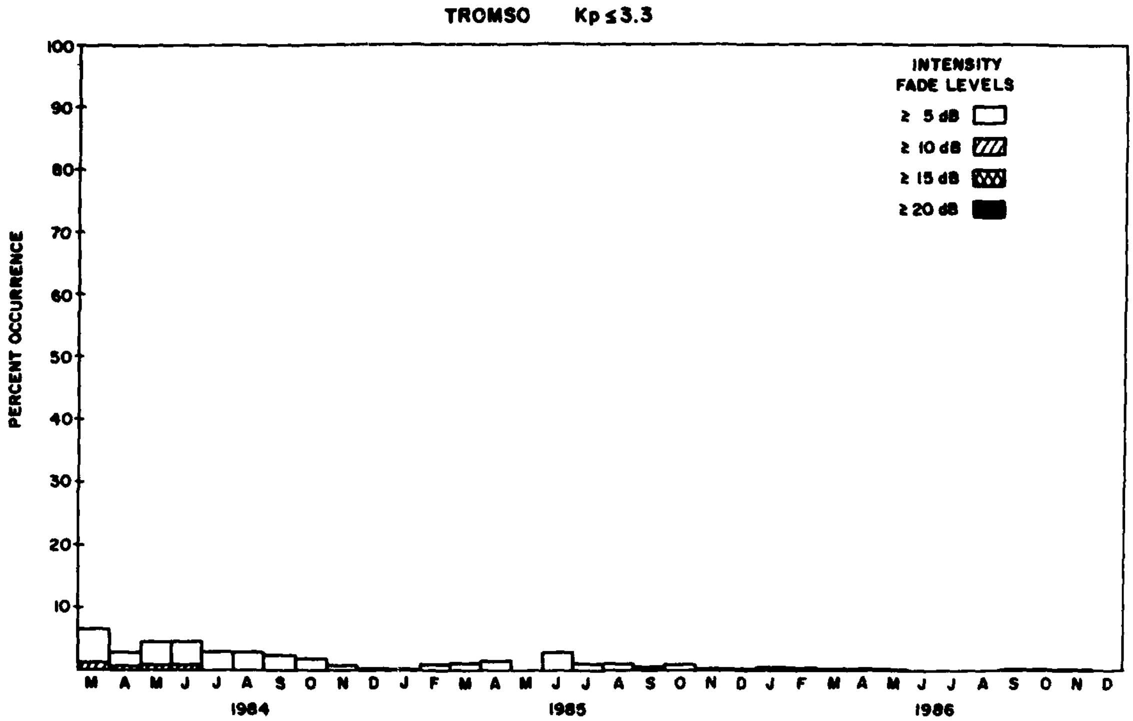

Fig. 5b. Intensity scintillations at 250 MHz observed at Tromsø for $Kp < 3.3$ under low-sunspot conditions between 1984 and 1986.

speed at equatorial locations in the postsunset period ranges between 100 and 200 m s^{-1}, the above decorrelation time corresponds to spatial correlation length of only 10–20 m.

The effects of strong scattering resulting in decreased spatial correlation lengths are not confined to the VHF (250 MHz) band but extend to the L band as well. At Ascension Island, where the 1.54-GHz transmissions from the Marisat satellite often suffer strong scattering, decorrelation times as small as 0.4 s are obtained in the postsunset period under sunspot maximum conditions [*Su. Basu et al.*, 1983]. For typical irregularity drift speeds in the range of 100–200 m/s, the spatial correlation lengths at 1.54 GHz may thus be reduced to values as small as 40–80 m. This is an order of magnitude smaller than the 1 km effective aperture length of typical L band synthetic aperture radar (SAR) systems. Thus this will adversely affect the resolution of the radar system. The above result assumes that the altitude of the SAR system is at least 800 km so that the bulk of the F region ionization lies below the radar and thereby can degrade the system performance.

Goose Bay and Tromsø

We next consider scintillation statistics in the auroral oval. Measurements were available using several polar beacon satellites at 250 MHz from Goose Bay in the North Atlantic sector for sunspot maximum conditions, while data were available from Tromsø in the Scandinavian sector for sunspot minimum conditions. The range of latitude covered for both stations is given in Table 1. We note that both are auroral locations only for nighttime hours between 2200 and 0400 MLT [*MacKenzie et al.*, 1987] with the higher intersection latitudes providing higher probability of scintillations during magnetically quiet conditions ($Kp < 3.3$). The polar beacon satellites used for these measurements also do not provide uniform local time coverage. In addition, different latitude ranges were explored at different times of the year. Thus time periods for which the higher intersection latitudes were sensed around midnight would be favored for higher scintillation occurrence. Unfortunately, there is no easy way of separating these different variables. The occurrence statistics

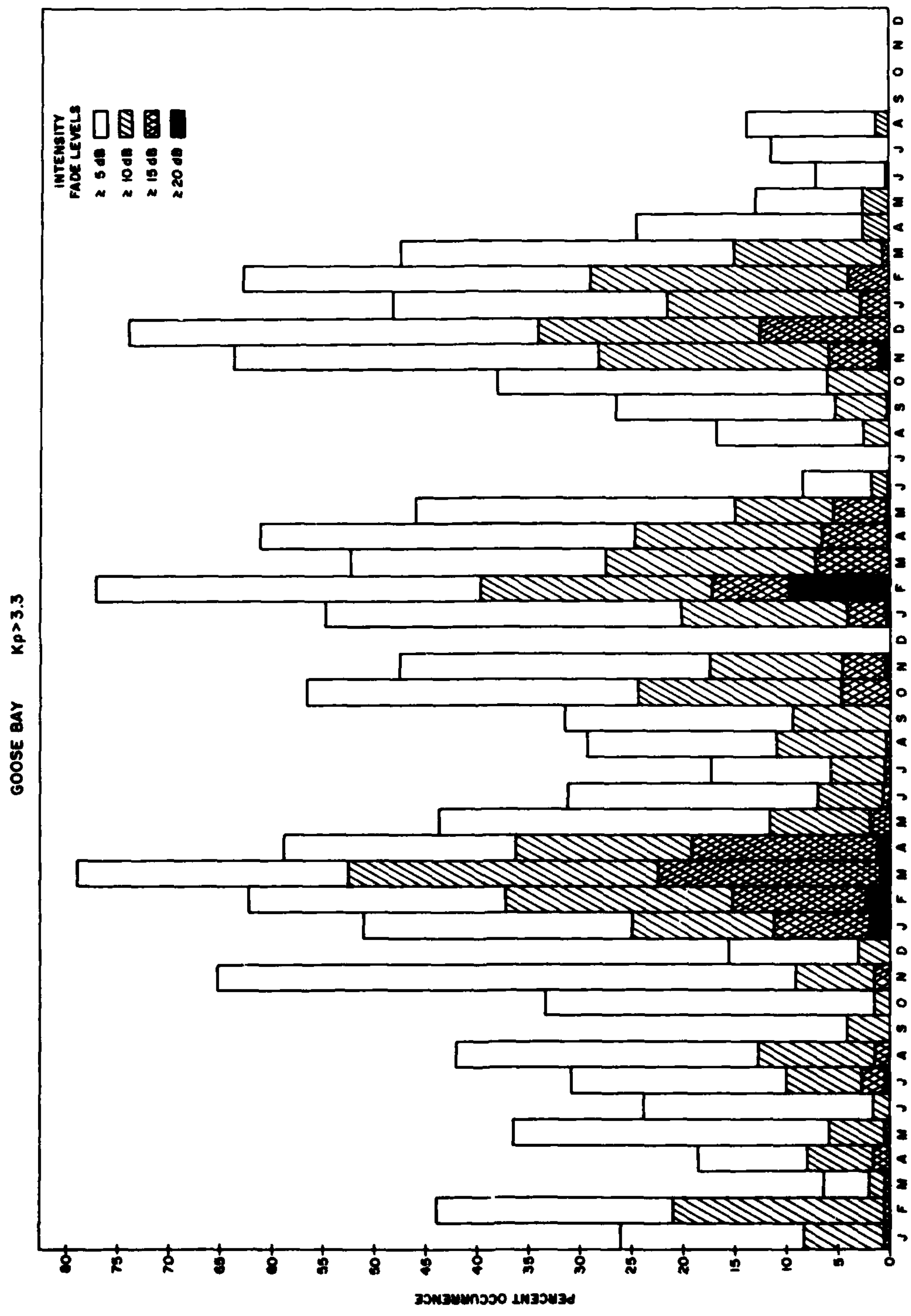

Fig. 5c. Same as Figure 5a except for $Kp > 3.3$.

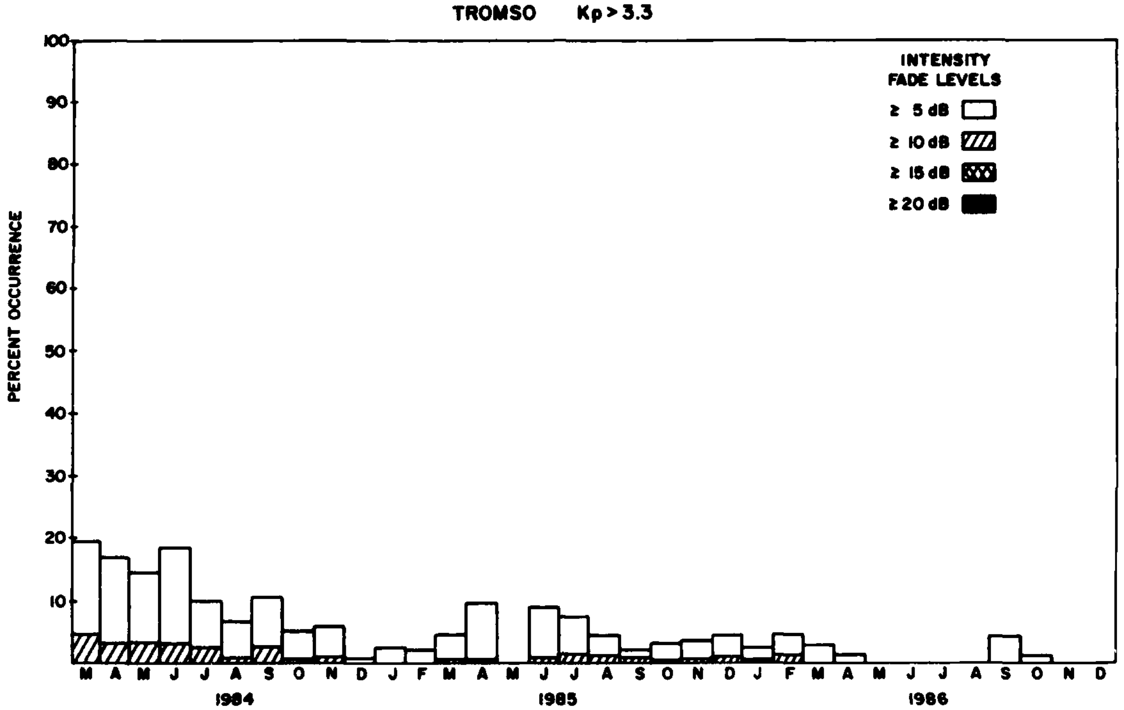

Fig. 5d. Same as Figure 5b except for $Kp > 3.3$.

should be viewed within the framework of these constraints.

Figures 5a and 5b illustrate the drastic variation of intensity scintillations at 250 MHz with sunspot cycle under magnetically quiet conditions ($Kp < 3.3$). As mentioned earlier, the apparent seasonal modulation seen in the Goose Bay data is probably related to the latitude variation of the ionospheric intersection regions in the June solstice in comparison to other seasons. The Tromsø data show extremely low occurrence. The corresponding occurrence characteristics for high magnetic activity are shown in Figures 5c and 5d. Magnetic activity increases scintillation occurrence and magnitude during both solar maximum and minimum periods. Further, the reduction in the apparent seasonal modulation of scintillations at Goose Bay with increasing magnetic activity supports the effect of varying intersection latitude mentioned earlier: It is well known that the scintillation boundary moves equatorward during magnetic disturbances [*Su. Basu and Aarons*, 1980].

One of the most prominent features of auroral scintillations is the existence of magnetic L shell–aligned irregularity sheets which gives rise to enhanced phase scintillations when the ray path to a satellite becomes aligned with the local L shell [*Fremouw et al.*, 1977; *Rino et al.*, 1978]. In Figures 6a and 6b we show that the same type of irregularity anisotropy (namely, sheetlike) is present during both sunspot maximum and minimum conditions. Wideband satellite data at 137 MHz obtained at Goose Bay in 1979 are used for Figure 6a [*Su. Basu et al.*, 1981], and the geometrical enhancement is observed in the 63°–64° invariant latitude bin, while similar data using the HiLat satellite at Tromsø are used for Figure 6b [*S. Basu et al.*, 1987b] and show an enhancement in the 65°–67°N invariant latitude bin. It should be noted that the higher magnitudes of σ_ϕ observed in the HiLat data result from the use of 30-s detrend intervals in comparison to 10-s used for Wideband data analysis. Since both satellite scan velocities are approximately 3 km s^{-1}, these detrend periods allow phase scintillation computations to be made over 90 km of orbital path for HiLat and only over 30 km for Wideband.

Thule

The occurrence of different levels of intensity scintillation fades at 250 MHz is shown for the period

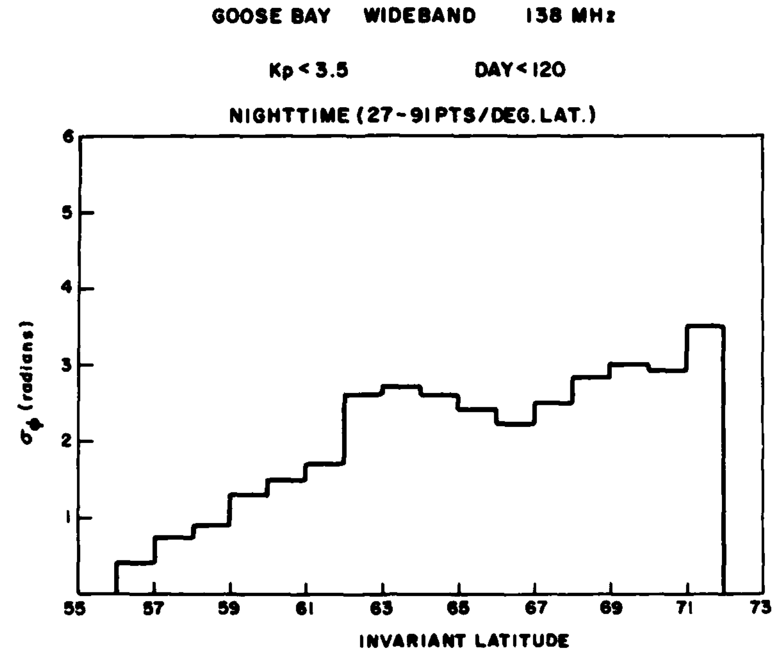

Fig. 6*a*. Latitude variation of scintillations at 138 MHz observed at Goose Bay during the vernal equinox of 1979 using the Wideband satellite. Note nighttime scintillation enhancement in the 63°–64° invariant latitude bin caused by sheetlike irregularity anisotropy in the nighttime auroral oval.

1979–1986 in the bottom panel of Figure 7. Because of lack of strong diurnal variation, all 24 hours of observations are included. The drastic variation of occurrence and magnitude of scintillations with sunspot number, shown in the top panel, is evident. It is noted that intensity fades of 20 dB occur ~50% of the time under solar maximum conditions in 1979 and fades as low as 5 dB occur less than 5% of the time under solar minimum conditions in 1986. It has been discussed earlier by *Su. Basu et al.* [1985] that the reduction in scintillations during the June solstice arises not from a reduction of the background density but rather from a drastic decrease in the irregularity amplitude at kilometer scales, possibly in the presence of underlying *E* region conductivity [*Aarons et al.*, 1981*b*; *Vickrey and Kelley*, 1982; *Heelis et al.*, 1985].

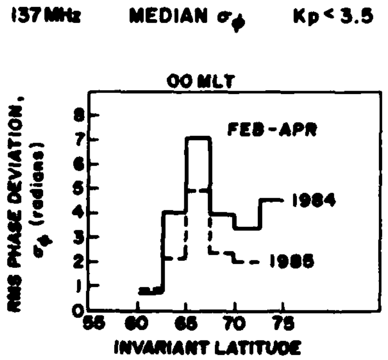

Fig. 6*b*. Same as in Figure 6*a* except that the station is Tromsø, the satellite is HiLat, and the years are 1984 and 1985. For Tromsø the geometrical enhancement for sheetlike irregularities occurs in the 65°–67.5° invariant latitude.

The phase and intensity scintillation statistics during a sunspot maximum period are reproduced in Figure 8 from *S. Basu et al.* [1987*a*]. Little diurnal variation is seen, with median values of σ_ϕ at 244 MHz (with 82-s detrend) being 3 rad and the upper decile being 12 rad. It should be noted that in the high-latitude environment large convection velocities are responsible for large σ_ϕ magnitude when a quasi-geostationary satellite is used as a source [*Su. Basu et al.*, 1985]. However, in spite of large convection velocities the smallest decorrelation time observed at Thule is approximately 0.3 s in comparison to 0.1 s at Ascension Island, where the scattering strength is much larger. It indicates that higher levels of turbulence at low latitudes decrease the decorrelation time, although the convection velocity does not exceed 200 m s^{-1}. Although phase scintillation measurements

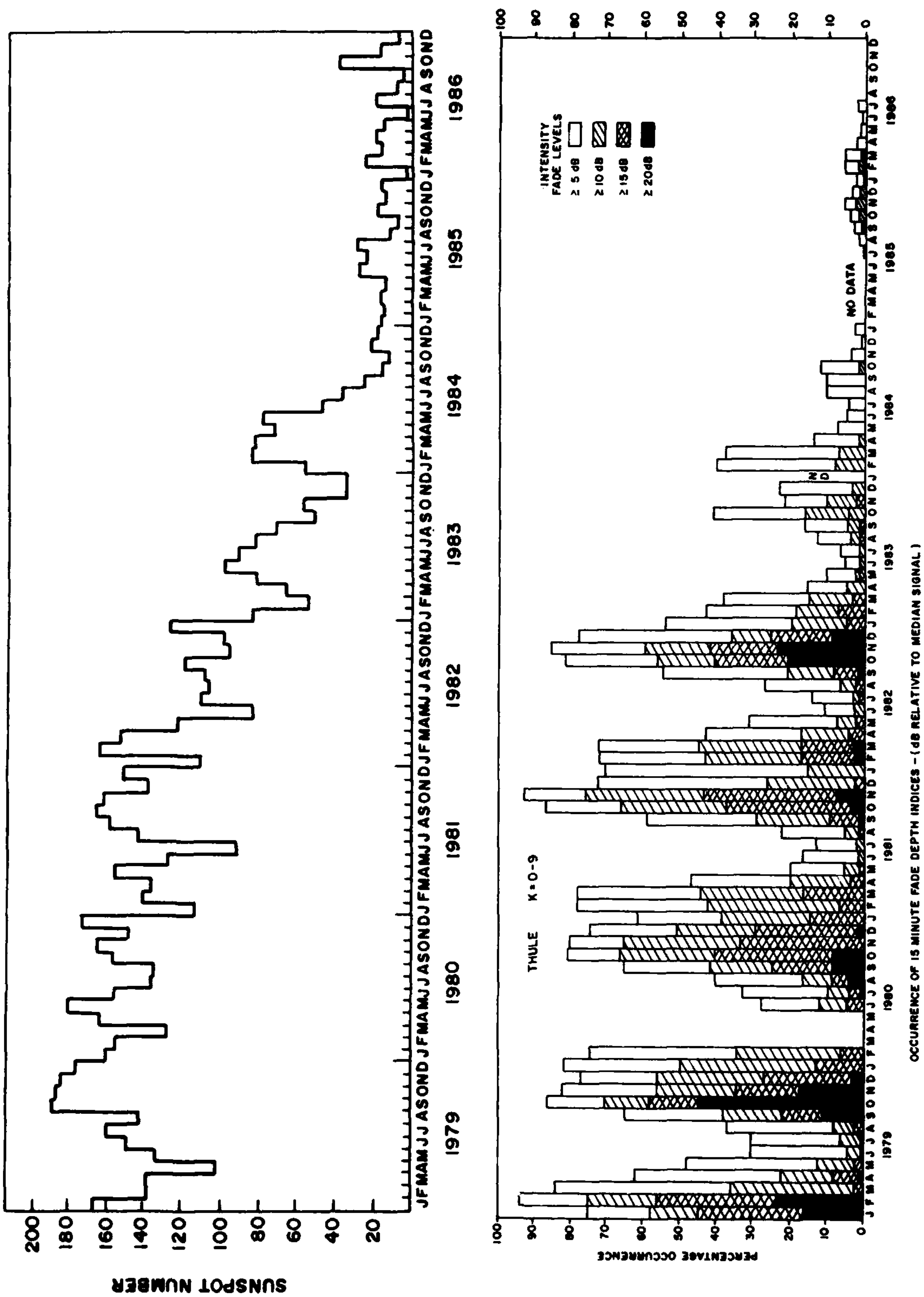

Fig. 7. Occurrence of 5-, 10-, 15-, and 20-dB fades at 250 MHz observed at Thule during the period 1979-1986. All local times and all magnetic activity data are included. Figure 1 is repeated in the top panel to emphasize the dependence of scintillation occurrence and magnitude on the sunspot cycle.

were continued into the low-sunspot period, median σ_ϕ magnitudes hardly ever exceeded 1 rad at 250 MHz, which is the threshold of these measurements, and thus the data are not shown. It should also be mentioned that the Thule measurements at 250 MHz indicate that scintillation activity did not vary much during 1979–1982 in spite of the variation of solar activity during that period. However, scintillations started to decrease rather abruptly with further reduction of solar activity after 1982. It is not clear if there is indeed a threshold level of solar activity above which solar conditions lose their control over irregularity magnitude and their formation. Alternatively, this may be an artifact of saturated scintillation at 250 MHz.

Recently, *L* band scintillation and total electron content measurements at Thule have been started by the use of global positioning satellites. Very limited data have been published which indicate that ~3-dB fluctuations at *L* band frequency have been observed at high elevation angles in 1984 [*Weber et al.*, 1986]. These measurements will be useful in the next sunspot maximum period, particularly when 250-MHz scintillation becomes saturated.

SUMMARY

The global occurrence characteristics during sunspot maximum and minimum periods are summarized with the help of the schematic diagrams shown in Figure 9. The left-hand panel of the figure shows the scintillation activity during the sunspot maximum period. The activity level is expressed in terms of actual *L* band observations at the equator and extrapolations from 250-MHz observations at higher latitudes. The diagram identifies three major regions producing scintillations, namely, the region around the magnetic equator in the postsunset period, the nightside auroral oval and dayside cusp, and the region within the polar cap at all local times. The most disturbed region corresponds to the northern and southern crests of the equatorial anomaly where the magnetic dip is approximately 30°, with more moderate levels of scintillations being observed at the magnetic equator. The generation of the equatorial irregularities in the postsunset hours and the occurrence of a secondary maximum of *F* region ionization [*Anderson and Klobuchar*, 1983] at this time combine to produce such enhanced activity in this region. The diagram shows that the gigahertz scintillation activity is much more moderate at the magnetic equator, as was determined in the present study and earlier studies [*Su. Basu et al.*, 1980; *S. Basu et al.*, 1986].

The activity level at high latitudes is much more moderate than that at the equator. Among the two high-latitude regions, the polar cap is probably more active than the auroral oval. In the polar cap, blobs of structured plasma convected from the dayside cusp and polar *F* region arcs generated by particle precipitation have been identified as sources of scintillation activity [*Weber et al.*, 1984; *Weber and Buchau*, 1981; Su. Basu et al., 1988]. The dayside cusp has also been found to be a seat of significant scintillations [*Vickrey et al.*, 1985]. In the nightside auroral oval the activity level is more moderate than in the polar cap, as indicated in the diagram. In contrast to the magnetic equator, the greater variability of ionospheric drift at high latitudes changes the rms phase deviation and decorrelation times for a given level of intensity scintillation.

The right-hand panel represents the activity level during the sunspot minimum period. A drastic reduction of scintillation activity in all three regions is indicated. The latitudinal extent of equatorial scintillations is also reduced. Near the magnetic equator, scintillation levels of 5 dB at *L* band become rather uncommon. In the polar cap, 5-dB fade levels at 250 MHz are attained only 10% of the time, whereas at auroral stations scintillation magnitudes at 250 MHz rarely exceed 5-dB levels. At high latitudes, rms phase deviations at 250 MHz do not generally exceed 1 rad, which is the sensitivity of our current receivers.

It is obvious that ionospheric scintillations encountered during the solar maximum period are severe enough to be of concern in the design of radar and communication systems. The drastic reduction of scintillation occurrence at all locations during sunspot minimum is rather intriguing in view of the different instability mechanisms operative at high and low latitudes and thus points to the background density as the major modulating factor. From the point of view of successful scintillation modeling, it is important to determine whether the variation of the background *F* region ionization density with solar cycle is large enough to explain the observed scintillation behavior or whether it is necessary to postulate variation of irregularity parameters as well. At the equator, where irregularity generation is better understood, it has been shown that the high altitude of the *F* layer seen during solar maximum years helps the seeding and growth of the Rayleigh-Taylor

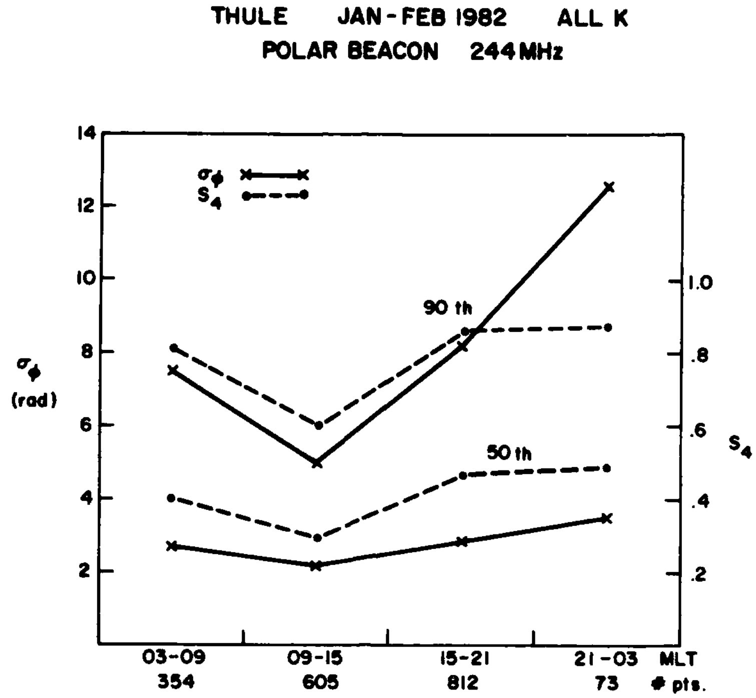

Fig. 8. The median (50th percentile) and 90th percentile values of phase and intensity scintillations at 244 MHz in terms of four 6-hour MLT blocks observed at Thule.

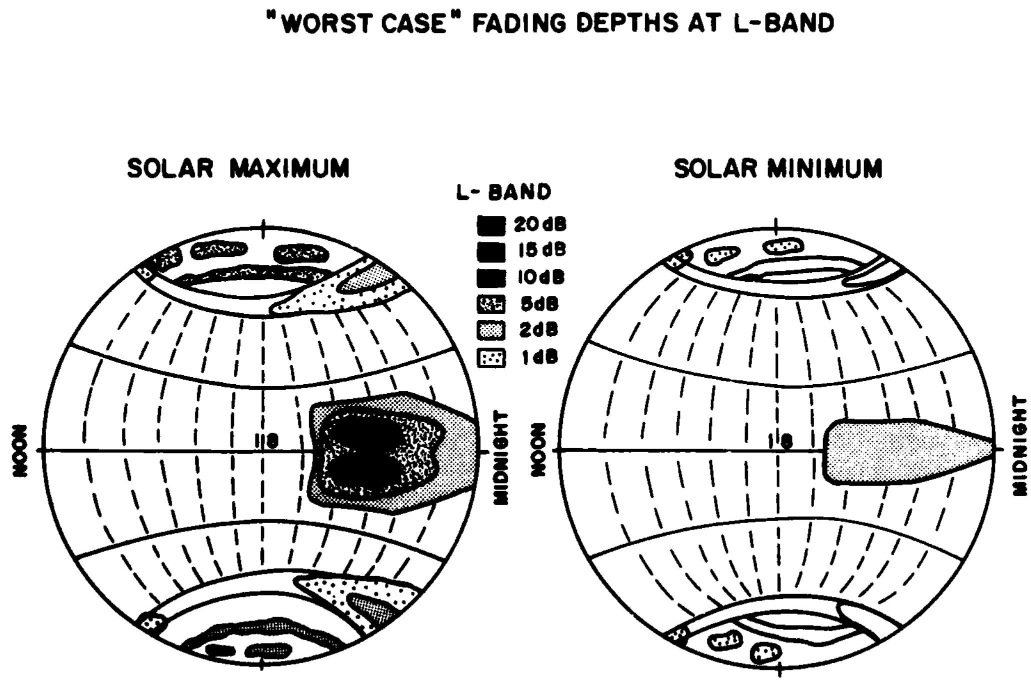

Fig. 9. Global variation of scintillation fades during solar maximum and solar minimum.

instability [*Ossakow*, 1981] and may explain the increased occurrence of scintillations. It is interesting to note that the semiempirical low-latitude ionospheric model developed by *Anderson et al.* [1987] predicts an order of magnitude variation of background ionization density at the anomaly crest but only a factor of 2 variation at the magnetic equator. The observed variation of scintillation magnitudes as a function of solar cycle agrees well with these predictions. At high latitudes, on the other hand, where a plethora of instabilities may operate [*Keskinen and Ossakow*, 1983], it is very difficult to determine the extent to which each instability process may be affected by the solar cycle.

Acknowledgments. We thank the Danish Commission for Scientific Research in Greenland for permission to conduct ground experiments at Thule Air Base under Project 23-86. In addition, we thank the Canadian Marconi Company for assistance in obtaining the Goose Bay data. The Tromsø measurements were made with the assistance of personnel at the Tromsø Telemetry Station, while Huancayo data were kindly provided by the Instituto Geophysico del Peru. The work at AFGL was supported in part by Air Force Office of Scientific Research task 2310G9. The work at Emmanuel College was supported by AFGL contract F19628-86-K-0038.

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An extensive VHF/UHF scintillation data base covering the frequency range of VHF to a few gigahertz has been utilized to determine the magnitudes of phase and intensity scintillations and their temporal/spatial structures during the sunspot maximum and minimum periods. The equatorial portion of the study has been based on geostationary satellite observations at Huancayo, a station on the magnetic equator, and at Ascension Island, which is an equatorial anomaly station having an extremely disturbed irregularity environment. The high latitude part of the study is based on quasi-stationary satellite measurements at a polar cap location (Thule) and two auroral locations (Goose Bay and Tromso). The Tromso observations are augmented with the Defense Nuclear Agency HiLat satellite beacon measurements during the solar minimum period. The data indicate a strong solar cycle control of scintillation activity at all locations, resulting in a drastic reduction of the

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